Thermal Development of the Mars 2020 Enhanced Engineering Cameras

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What is an Engineering Camera?

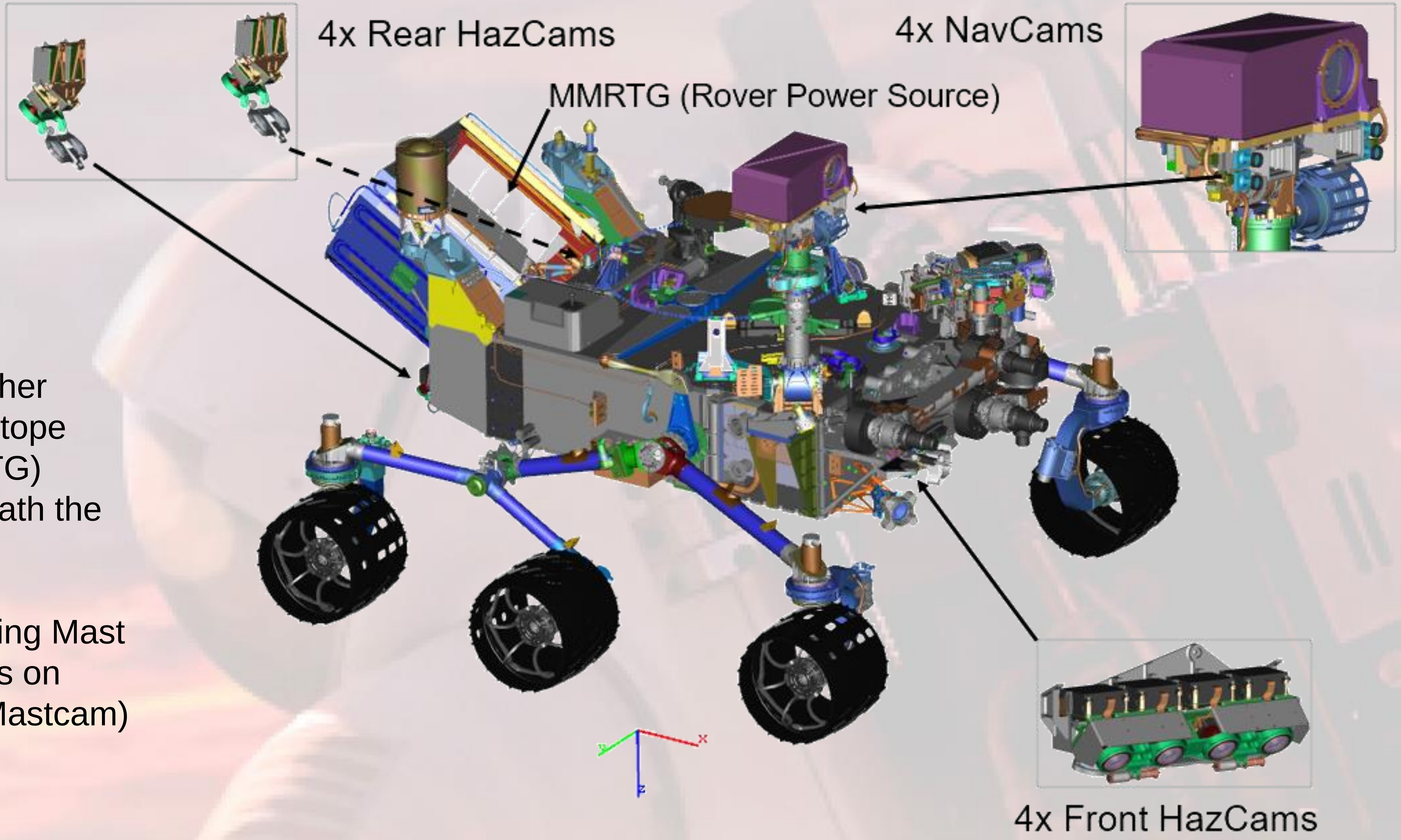
- Although typically several cameras fly on each Mars surface mission, the engineering cameras (ECAMs) are a subset of cameras used for spacecraft operations, as opposed to those used for scientific objectives

- Some spacecraft operations that the ECAMs support:
  - Autonomous rover driving on Mars
  - Robotic Arm (RA) positioning
  - Monitoring and targeting of hardware

- The first generation of ECAMs were developed for use on the Spirit and Opportunity rovers of the Mars Exploration Rover (MER) mission that launched in 2003
  - Total of 6 ECAMs per MER rover:
    - 4 Hazard Avoidance Cameras (HazCams): provide stereo imaging of environment to detect obstacles
    - 2 Navigation Cameras (NavCams): provide stereo and panoramic imaging of the rover's surroundings to aid in navigation

Mars Science Laboratory (MSL) ECAMs

- The six surface MER ECAMs were reused on MSL with the same exact design, except in larger quantities and slightly higher heater powers



<u>12 total ECAMs</u>

8x HazCams:

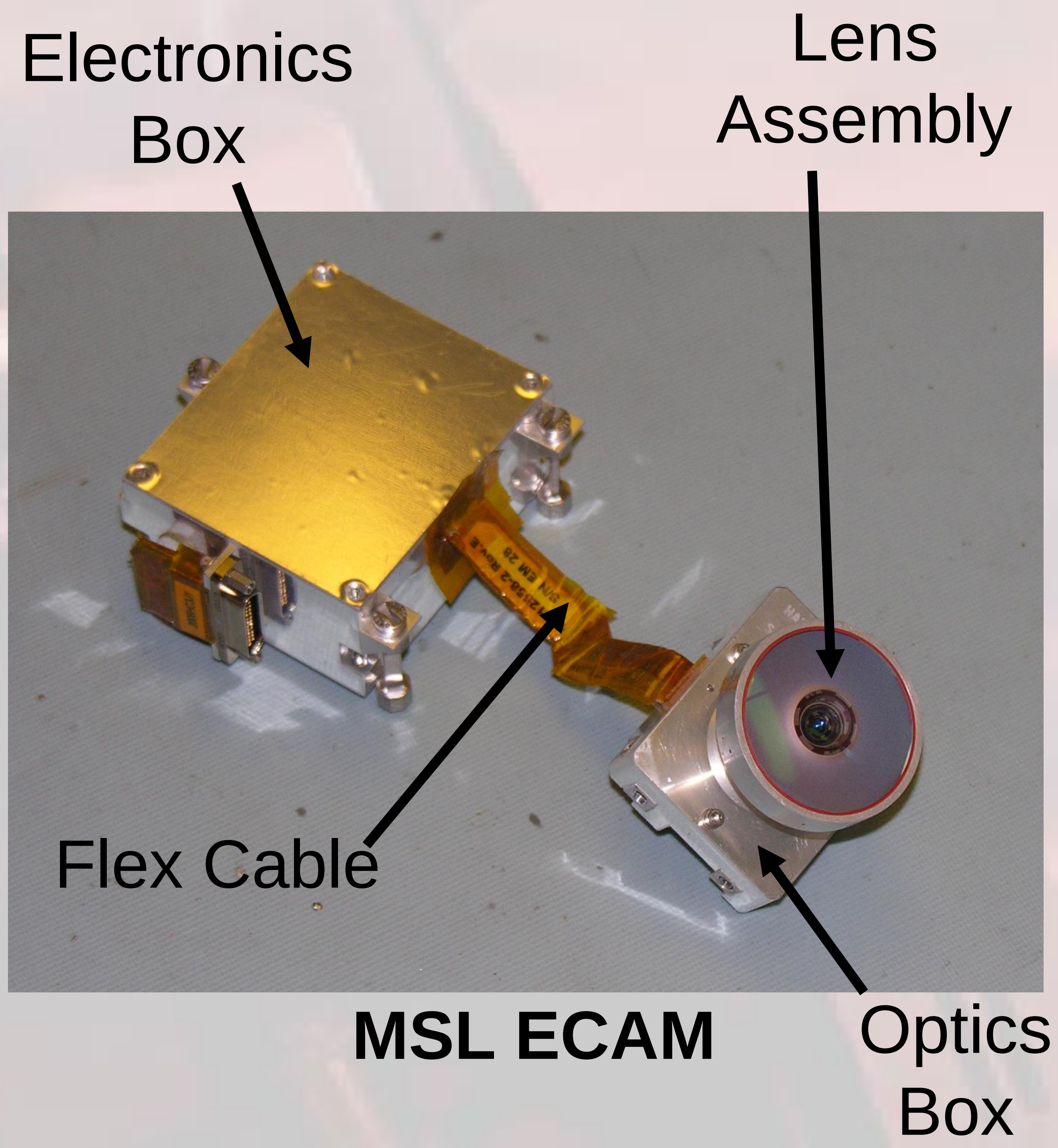
- 4x at the rear of the rover, on either side of the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG)
- 4x at the front of the rover, beneath the Robotic Arm

4x NavCams:

- At the base of the Remote Sensing Mast (RSM) head, each pair of cameras on either side of the Mast Camera (Mastcam)

Mars Science Laboratory (MSL) ECAMs

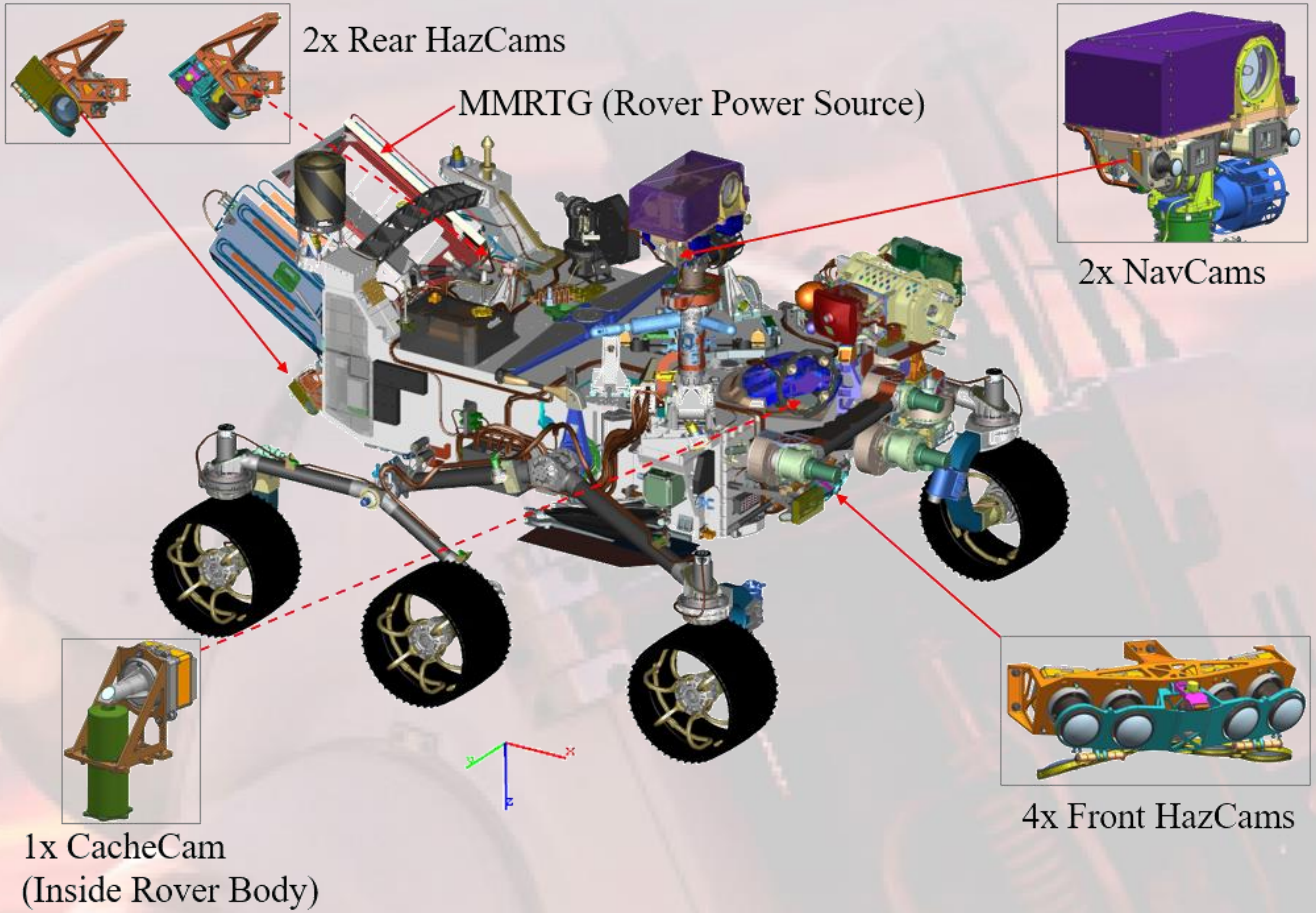
- The MSL ECAMs operated as stereo pairs, with two front HazCam stereo pairs, two rear HazCam stereo pairs, and two NavCam stereo pairs
  - The redundancy was a contingency; in the event of a camera failure in the one of the pairs, the redundant pair could be used instead
- NavCams and HazCams were nearly identical in architecture, only differing by their lens designs (HazCam lens was more massive with a smaller focal length and larger field of view)
- Architecture was a two-box design: one box for the optical components (lens assembly and detector) and the other box for camera electronics, with both boxes connected via flex cable
- Detector was a charge-coupled device (CCD) that imaged in black and white with a resolution of 1024 x 1024 pixels
- Operational power of the ECAMs was 2.75 W
- Warmup heaters were resistors on the electronics, totaling 3.5 W of power
- Total of 26 ECAMs were built in the mission program – only 12 flew on the mission
  - 4x were built as flight spares
  - 10x were built as engineering units



MSL ECAM

Mars 2020 Enhanced Engineering Cameras (EECAMs)

- The technology of the MER/MSL ECAMs is well over a decade old and obsolete, so the Mars 2020 mission is introducing a new, more powerful camera called the *enhanced* engineering camera (EECAM)



9 total EECAMs

6x enhanced HazCams:

- 2x at the rear of the rover, on either side of the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG)
- 4x at the front of the rover, beneath the Robotic Arm

2x enhanced NavCams:

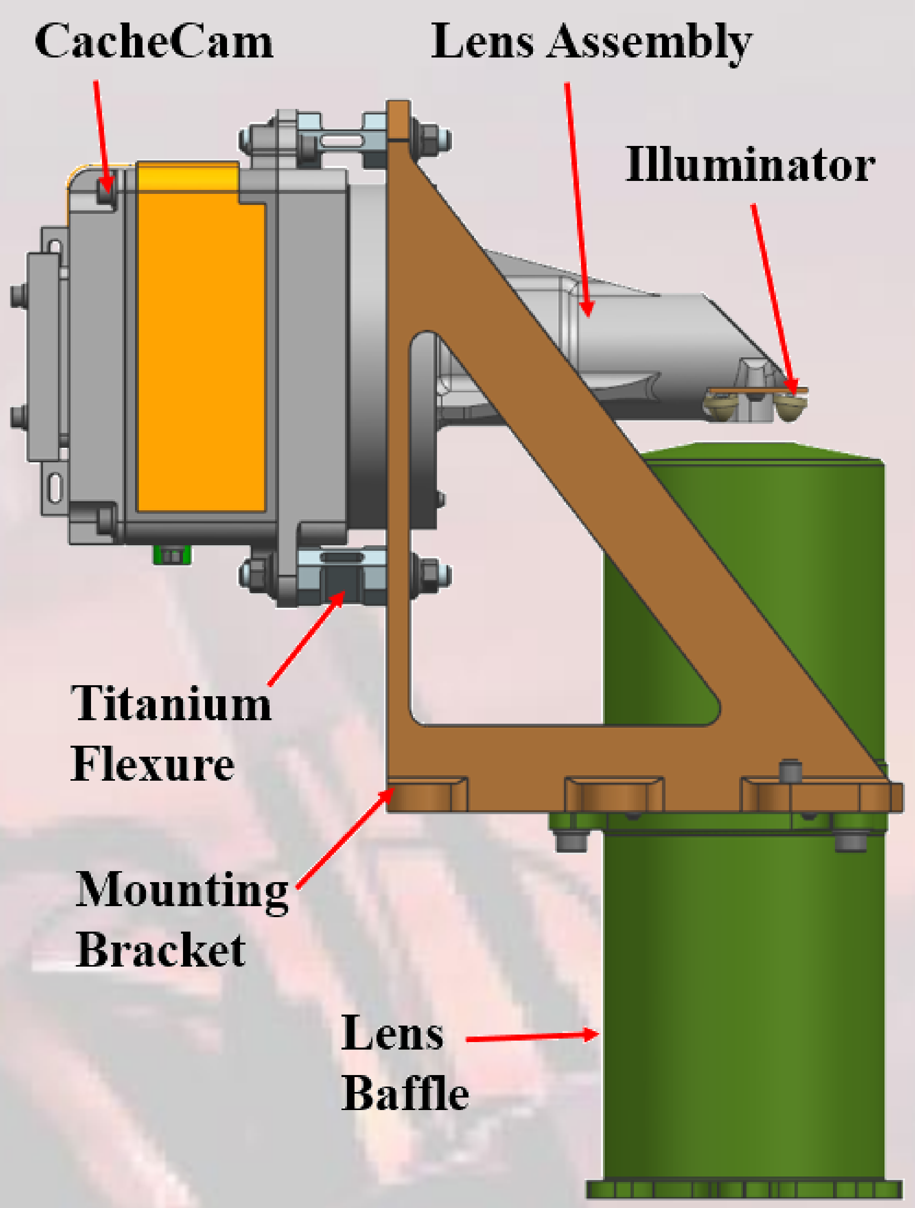
- At the base of the Remote Sensing Mast (RSM) head

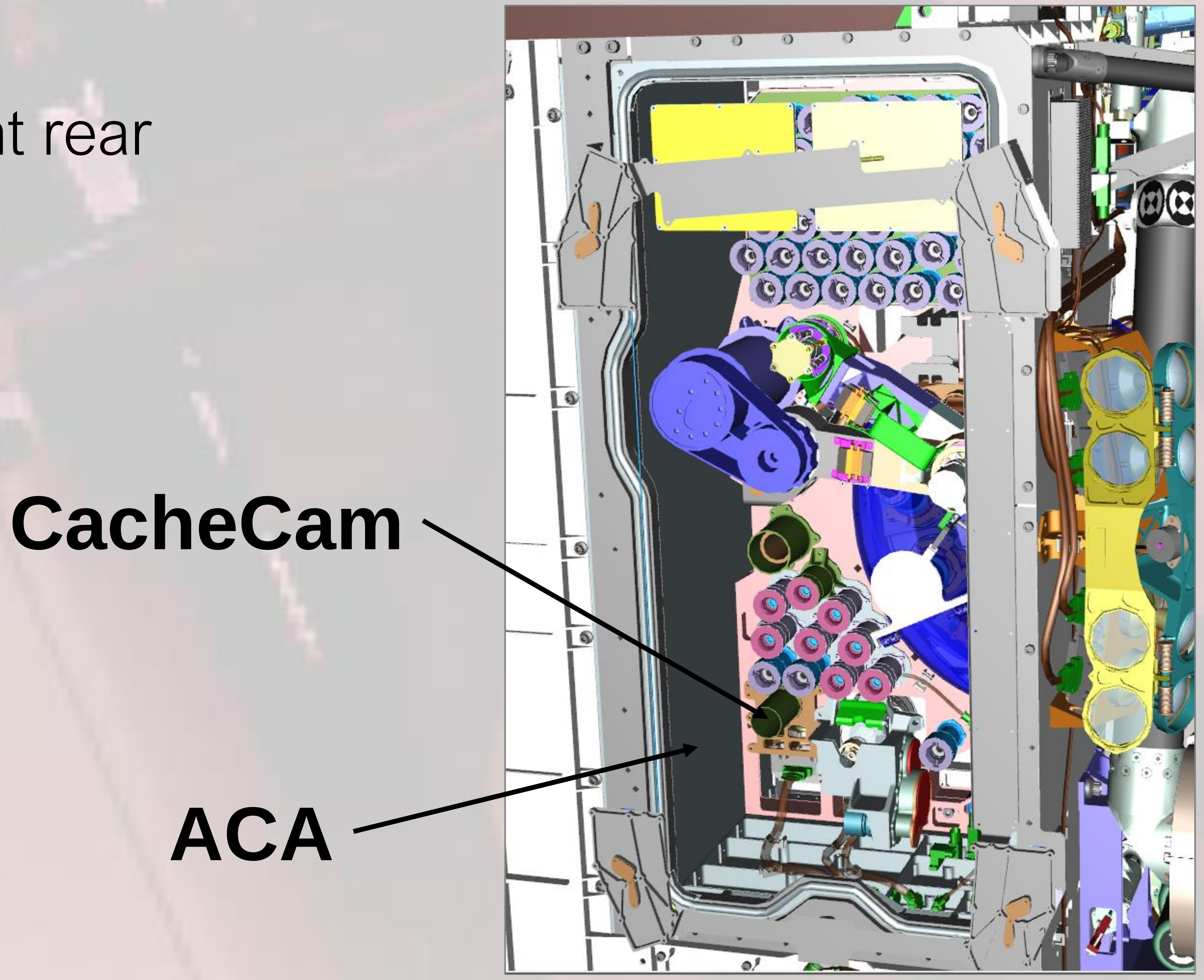
1x newly designed CacheCam (Caching Camera)

- Inside the Adaptive Caching Assembly (ACA) as part of the rover's new Sample Caching Subsystem (SCS)

Mars 2020 Enhanced Engineering Cameras (EECAMs)

- The Mars 2020 rover's SCS is designed to excavate rock samples, store them in sample tubes, and deposit them on the ground for potential future return – the new CacheCam's objective is take images of any obtained samples.
- Reduction in the number of HazCams and NavCams from the MSL design is due to a shift from the original EECAM CCD detector to a larger CMOS (complementary metal-oxide semiconductor) detector that can image in color with a higher resolution of 5120 x 3840 pixel resolution
  - To accommodate this much larger detector and the electronics to support it, the original two-box design of the ECAMs had to merge into one and increase in size
  - This change to a single-housing design increased the overall volume of the EECAM compared to the ECAM, reducing the number of cameras that could fit within the allocate volume on the rover
- As with the MSL ECAMs, the Mars 2020 EECAMs have identical camera bodies and only differ by their lens assemblies
- The Mars 2020 EECAMs similarly operate as stereo pairs, but there are no longer any redundant rear HazCam and NavCam stereo pairs.
- Operational power of the EECAMs is 2.22 W
- Kapton warmup heater on the housing, totaling 20 W of power
- 25 total units will be built:
  - 9x flight units
  - 4x flight spare units
  - 3x qualification units
  - 9x engineering units





Environmental Factors and Assumptions

	Worst Case Cold (WCC)	Worst Case Hot (WCH)
Landing Site	Holden Crater (26˚S) Winter (L_s = 91˚)	Holden Crater (26˚S) Summer (L_s = 259˚)
Wind Speed	0 m/sec or 15 m/sec	0 m/sec
Rover Configuration	• Cameras facing west • NavCams point towards sky	• Cameras facing west • NavCams point towards sky
Optical Coating Degradation and % Dust Coverage	Beginning-of-Life (BOL) 0%	End-of-Life (EOL) 10% for Vertical and NavCam Surfaces 40% for Horizontal Surfaces
Bus Voltage	28V (minimum)	32.8V (maximum)
Camera Operation and Dissipation	Either: - Always off - Turned on after warmup	2.22 W for each EECAM (+0.75W for CacheCam Illuminator) **Analyzed Use Cases**: Front Haz/NavCams – On 2 hours Rear HazCams – On 5 minutes CacheCam – On 20 minutes

Thermal Requirements

Operational Temperature Requirements

- The operational temperature requirements of the MSL ECAMs were straightforward: For both the MSL HazCams and NavCams, the operational allowable flight temperature (AFT) ranges were: -128˚C to 50˚C for the optics box (CCD detector and optics assembly) and -55˚C to 50˚C for the electronics housing
- The temperature limits of the Mars 2020 EECAMs are much more complex:
  - The operational AFT range of all the EECAM camera bodies is similarly -55˚C to 50˚C
  - The op. AFT range of the lens assemblies vary depending on EECAM type because of the more complex optical design over that of the MSL ECAMs
  - Mars 2020 lens assemblies need to be athermalized, a design process in which an optical system must have a stable optical performance over a range of temperatures. The difficulty in athermalization is from the *magnitude* of the temperature range, not the nominal limits.
- Since the lens designs are all different and the EECAMs are located on various parts of the rover, the lens assemblies do not see the same operational temperature ranges.
  - It was difficult to develop uniform temperature limits for all the cameras, so an operational AFT range of -55˚C to 50˚C was set as a starting point for all the EECAM lenses and was adjusted accordingly as detailed thermal analyses of the preliminary lens designs progressed

Camera	Component	Operational Allowable Flight Temperature, ˚C		Operational Qualification Temperature, ˚C	
		Minimum	Maximum	Minimum	Maximum
HazCam	Camera Body	-55	50	-70	70
	Lens Assembly	-95	40	-110	60
NavCam	Camera Body	-55	50	-70	70
	Lens Assembly	-75	30	-90	50
CacheCam	Camera Body	-55	50	-70	70
	Lens Assembly	-80	25	-95	45
	Illuminator	-80	50	-95	70

Thermal Requirements

Mounting Interface Requirements

All the EECAMs interface with the rover via mounting brackets, so two requirements are set to limit heat losses to the brackets during the warmup of the cameras

- Firstly, each camera is mounted to its bracket through three thermal isolators. There is a requirement for the Rover Mechanical Team that the total thermal resistance across those three isolators must be at least 14˚C/W. Initially, this requirement was set based on resistance values of existing isolator geometries that have flown on past Mars surface missions, but as the interfaces matured, this requirement was re-negotiated as necessary. The final isolators are titanium flexures.
- Secondly, since CO_2 gas conduction can be a significant contributor to heat losses at small gaps, a requirement states that the minimum gas gap between the cameras and adjacent hardware must be at least 4 mm (exceptions are analyzed on a case-by-case basis).

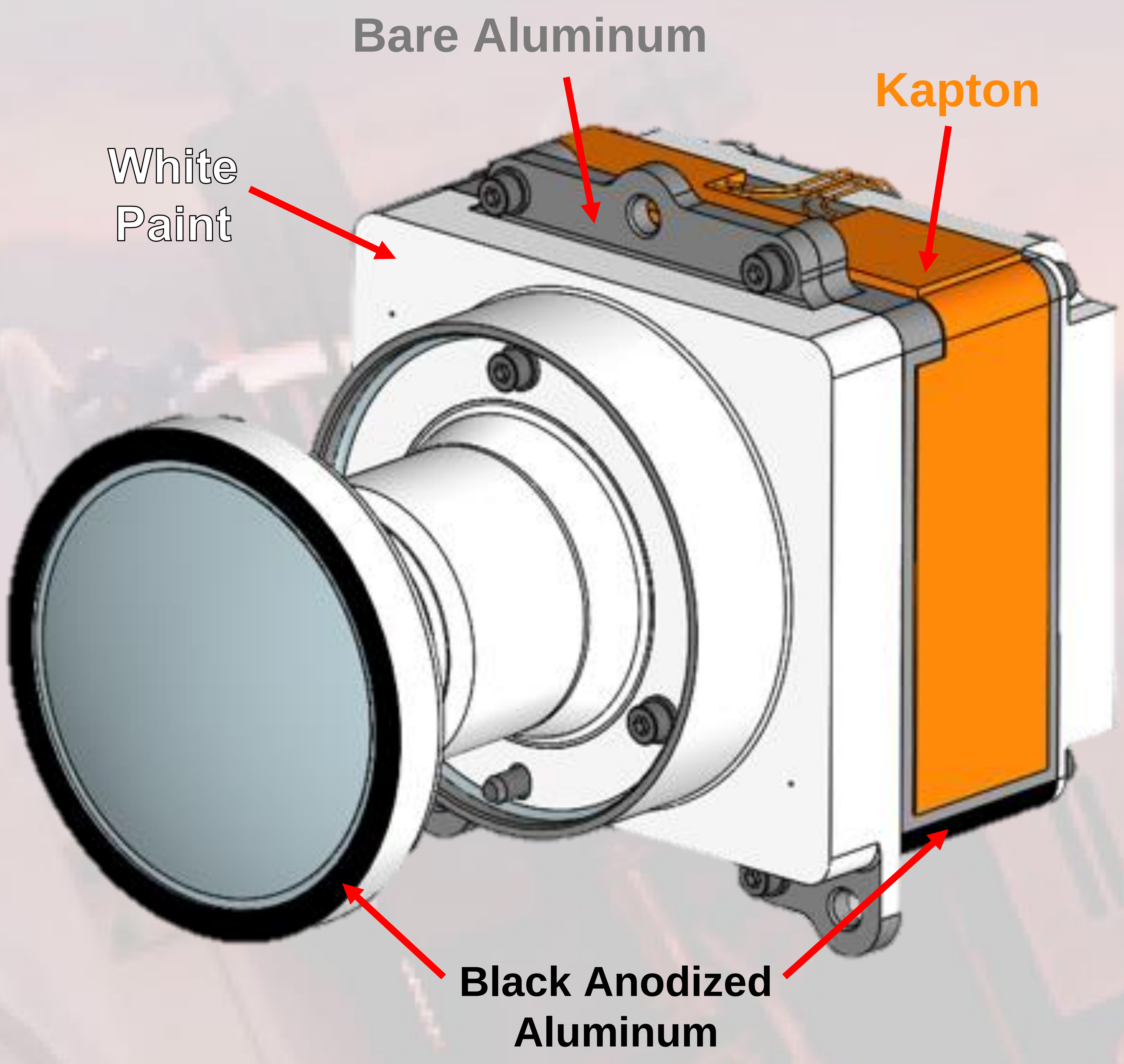
Operational Requirements

The Mars 2020 Flight System System Engineering Team has not placed any requirements on the warmup times, heater energy usage, or time of day of operations for the EECAMs

- Not very straightforward to do so
- If “heat-to-use” practice is too energy-expensive, the Operations Team would delay the start time or employ a “wait-to-use” strategy to allow the environment to warm up the hardware
- As a guideline, the Operations Team suggested that a warmup time of 1 hour or less would be acceptable, while a warmup time of ~30 minutes would be ideal

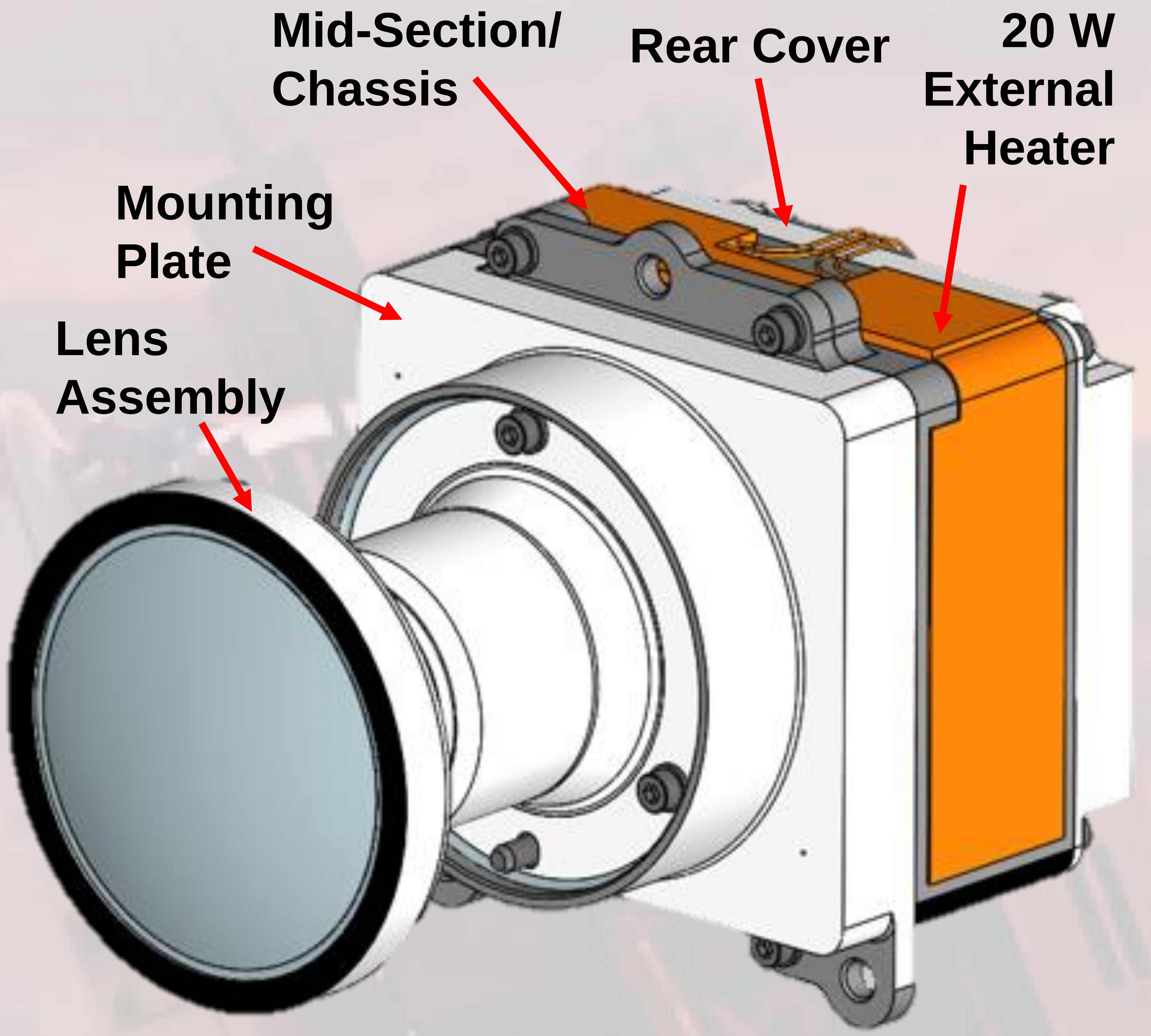
Thermal-Optical Coatings

- Major surface coatings of the HazCam are shown to the right (HazCam and NavCam coatings are identical)
  - Primarily white paint to reflect sunlight in WCH environment
  - Heater is made of Kapton and applied to bare aluminum surface
  - Some smaller areas are black anodized
  - HazCam and NavCam mounting brackets are also painted white
- CacheCam does not have any white paint since it is located inside the ACA which does not see any sunlight
  - Ideally would have same coatings as Haz/NavCams for hardware interchangeability, but this is impossible due to contamination requirements in the ACA
  - Since ACA is the primary region where storage of rock samples occurs, stringent requirements forbid organics inside the ACA (unless absolutely necessary) because of the risk of sample contamination
  - Potential white-painted areas on the CacheCam body are left as bare aluminum, and the CacheCam lens exterior is black anodized

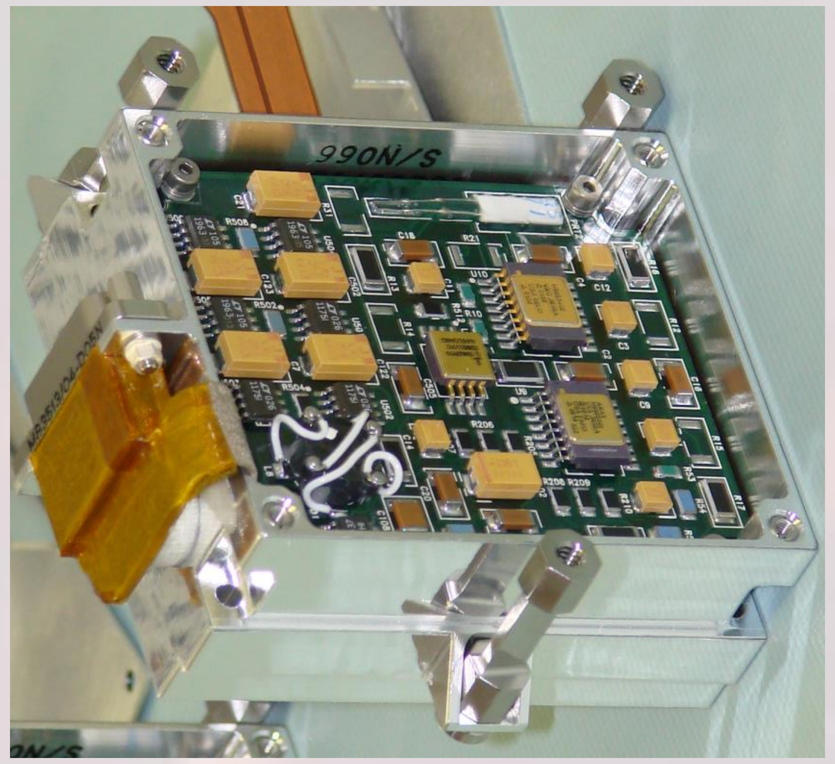


Heater Design

- The heater design approach is to place the largest heaters possible on hardware, as allowed by electrical limits of switches and area constraints of hardware to heat components as fast as possible
- MSL ECAMs had warmup heaters in the form of chip resistors on the circuit boards, totaling 3.5 W of power
- One of the most significant thermal design changes from the ECAM configuration is the change in heater power and location on the EECAM
  - Instead of chip resistors on the boards, a Kapton film heater with a power of 20 W located on the exterior of the mid-section/chassis is used
- EECAM heaters are controlled by flight software using PRTs
  - In case of failure, there are 2 PRTs per camera for redundancy, each one connected to one of the Rover Power and Analog Modules (RPAM-A and RPAM-B)
  - Since the NavCams, rear HazCams, and CacheCam do not have any camera redundancy, they each have redundant A and B-side heaters



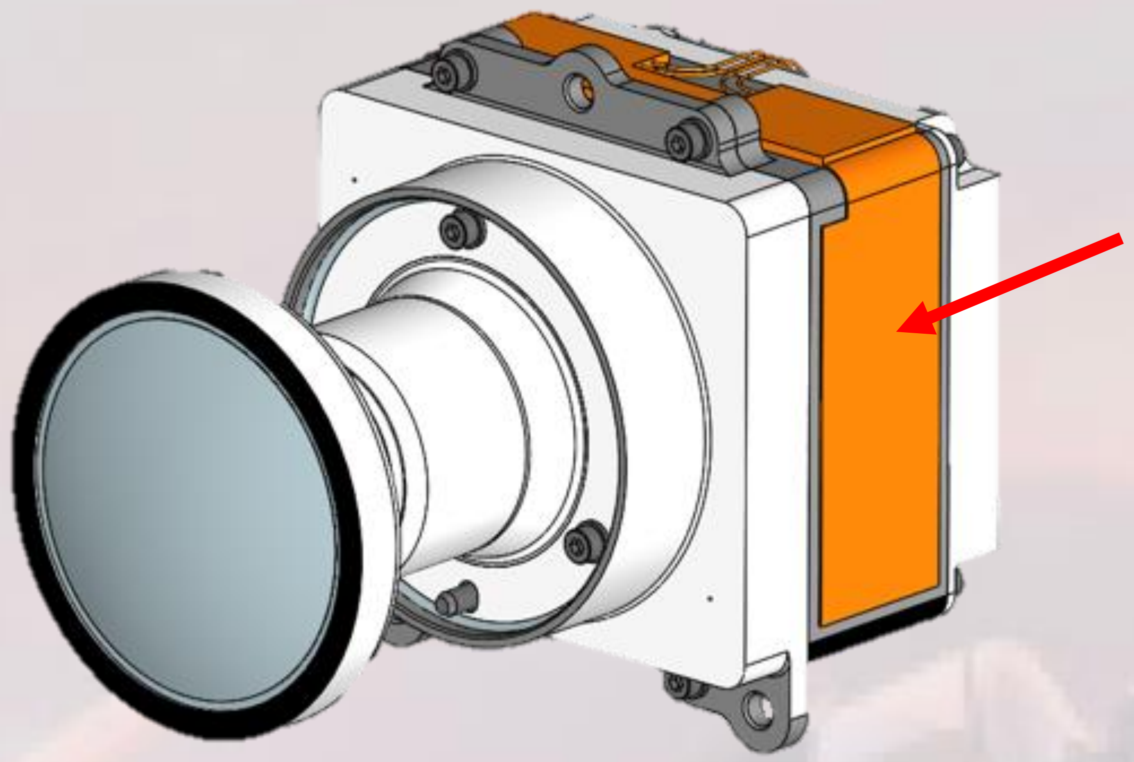
Pros & Cons of Resistive Heating on Boards (MER/MSL Design)



Chip resistors on boards, with boards isolated from housing

Pros	Cons
Puts heat where needed – at parts on board	Hot & cold case designs are incompatible; requires "optimized" thermal resistance from board to housing to minimize heater power while preventing overheat while operating (a problem on MSL)
Faster warmup – less mass to warm up, lower power heater, less energy consumption	Does nothing to bring lenses into operating temp range; would likely require external heater on lenses
Easy access to internal wiring & connector pins	Requires board area and Z height to accommodate chip resistors or Dale Ohm resistors – couples electronic board design & heater design
Lower heat loss to environment – less susceptible to wind & convective losses	Heat goes into board at discrete locations – must have sufficient copper in board to properly spread heat

Pros & Cons of Heating on Camera Housing (Mars 2020 Design)



Pros	Cons
Hot & cold case designs are compatible; increasing conductance from board to housing helps drive warmup heat into board in cold case and drive heat off the board in the hot operating case	Heater is not located specifically where temperature sensitive components are located
Heater on housing also helps to warm lenses into operational range	Warmup uses more energy – larger mass to warm up & increased heat leaks to environment
Heater does not consume board area; decouples heater design from electronics board design	Longer warm up times also leads to more energy consumption
Can use Kapton film heater to spread heat	More susceptible to convective (wind) heat loss since heater on housing is directly exposed to env't

Thermal Performance

	WCC, 15 m/sec Wind		WCH, No Wind	
Camera/Location	Warmup Time, minutes	Warmup Energy, W-hr	Max. Camera Housing Temperature, ˚C	Max. Lens Temperature, ˚C
Front HazCams	33.7	11.2	35.5	34.6
Rear HazCams	31.8	10.6	34.5	33.7
NavCams	25.9	8.6	25.6	23.8
CacheCam	27.9	9.3	17.1	19.2

- No AFT violations
- Front HazCams have the worst case warmup time of 33.7 minutes, so the goal of a ~30 minute warmup has been met
  - In comparison, the warmup time of the MSL ECAMs was anywhere between 10 to 15 minutes (depending on wind speed)
  - Although the warmup times of the EECAMs are about 2-3x longer than those of the ECAMs and the EECAM heater power is significantly higher, the warmup time and warmup energy usage are small enough that mission performance won't be significantly affected.
- Hottest camera temperatures occur amongst the front HazCams with a max camera housing temperature of 35.5˚C and a max lens temperature of 34.6˚C.
  - No overheat concerns with the Mars 2020 EECAMs as there were for the MSL ECAMs

Conclusion and Future Work

- The deviations from the “build-to-print” philosophy of the Mars 2020 Project have enabled a robust thermal design that allows a great improvement in optical performance over the previous generation of engineering cameras.

- The thermal design of the EECAMs is complete and was successfully presented by the Mars 2020 Flight System Thermal Team in a Detailed Design Review (DDR) in April 2017

- With the completion of its final reviews, the EECAM team has commenced fabrication, testing, and delivery of the flight hardware

- Next steps in the thermal development are to work on test plans/procedures and continue analysis for thermal characterization, thermal model correlation, and future Landing Site Workshops. Afterwards, the team will generate heater tables for mission operations.

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